Identification of the Inertial Model for Innovative Semi-Immergible USV (SI-USV) Drone for Marine and Lakes Operations

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***Abstract*— The proposed project shows the results obtained in the implementation and testing in lacustrine and marine environment of a nautical remote controlled vehicle with surface navigation and innovative features Semi-Immergible (SI-USV). This vehicle is based on a pending patent belonging to Palermo University (Patent Pending RM2012A000209 and Patent RM2014Z000060) concerning innovative semi-immersible vehicles (SI-Drone), that can be remotely controlled from the ground, air, satellite and sea also during the semi-immersible operation. Given its low draft, the electric powered vehicle, coupled with jet propulsion, makes it possible to navigate in shallow waters, coastal shipping or sandbars.**

This complete system SI-Drone can solve the typical logistic problem occurring in very shallow water contexts (such as ports, rivers, lacustrine environment and marine coastal), where the low depth of the water column (generally less than 10 mt) presents several challenges, including near-field effect and operability difficulties. Then, the proposed system can be used for applications in the fields of ports, lakes monitoring, organic fish - marine, hydrography, geology / geophysics, oceanography, underwater acoustics and environmental monitoring with particular attention to climate change impact indicators. This paper deal with two dimensional motion control of DRONES based on merging of Fuzzy/Lyapunov and kinetic controllers. A fuzzy kinetic controller generates the surge speeds and the yaw rates of each DRONE, to achieve the objective of the planar motion planned by the decentralized algorithm, and it ensures robustness with respect to perturbations of the marine environment, forward surge speed control and saturation of the control signals, while the kinetic controller generates the thruster surge forces and the yaw torques of all the DRONE. The Lyapunov's stability of the equilibrium state of the closed loop motion control system is proved based on the properties of the Fuzzy maps for all the underwater vehicles, so that the stabilization of each semi-immergible vehicle in the planned trajectory is ensured. The validity of this control algorithm is also supported by simulation experiments.

The procedures applied in the present article, as well as the main equations used, are the result of previous applications made in different technical fields that show a good replicability (1 – 4).

Keywords - si-usv, stadam centre, semi-immersible, vessel.

I. INTRODUCTION.

In recent, a number of unmanned surface vehicles (USVs) have been developed for bathymetric surveys, environmental monitoring and sampling, coastal defense, and supporting of Autonomous Underwater Vehicle (AUV) operations. In the context of increasing development of prototype USVs for research and civilian applications in the last four years the new Laboratory of System and Marine Technologies – La.Si.Tec.Ma. of Dept. DEIM of University of Palermo – Italy founded a feasibility study of an innovative, multipurpose, unmanned autonomous vessel for water and sea floor monitoring with the goal of providing, throughout the development of a prototype vehicle, an overview of the USV low cost innovative technologies for a new patented vehicle.

In the context of this paper the SI-USV [5] analyze the dynamics of the vehicle and its experimental tests innovative characteristic and technical performance of a semi-autonomous navigation, tele-guidance and tele-control of surface and semi immersion craft in coastal or protected waters on the basis of the requirements given by applications such as sea surface microlayer sampling or harbour surveying. The SI-USV or SI-DRONE [6] is a vehicle type USV with the capacity for marine navigation / aquatic gliding but also with the ability to be able to dive up to a few feet under water while remaining in constant communication with the Center of Supervision Telecontroller And Data Acquisition and Monitoring (STADAM Center) through a terrestrial or satellite radio link. It is easily transportable by road and can be quickly arranged beside features such as lakes, rivers, canals, but also to be able to navigate in marine environments and in adverse weather and sea conditions for monitoring and supervision of: coastal and lacustrine environments, monitoring lakes, organic fish - marine, hydrography, geology / geophysics, oceanography, underwater acoustics mapping and environmental monitoring of marine protected areas. The outcome of this project will be to provide demonstrated capabilities of a very low cost industrial remote PLC-Controlled Drone platforms and it is equipped with a GNU/Linux-based embedded real time system of instrumental and electrical telemetry (kinematic and power supplies) and a HDS Scructure Scan Sonar system for acoustic data acquisition with graphic remapping seabed capability (the testing version also to provide monitoring and ambiental capacity with CCTV PTZ cameras observers). In recent years there has been increasing interest in the use of underwater robotic vehicles to execute missions without direct supervisions of human operators [7]. The priority of the marine autonomous vehicles is to position itself, either tracking curves with autonomous navigation in the marine environment which has to be inspected, or near the structure of interest, against disturbances. Recently there has been a trend to use smaller autonomous underwater vehicles that use differential thrust for surge and yaw motion, with the advantage of increased maneuvrability in the yaw direction. In this cases the vehicles moves in the horizontal plane, but the vehicles above have limited control for the motion along the sway direction, so that it is underactuated, because the dimension of the control vector is less than the number of independent directions of desired motion and in general, falls into category of so-called non-holonomic systems. However

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motion control strategies for non-holonomic Unmanned Aerial Vehicles (UAV) [8] and ground cars [9] cannot be directly applicable to the case of marine vehicles, because they are subjected to complex hydrodynamic factors [4], they present unactuated dynamics and have a minimum surge control speed constraint that is greater than zero. Generally the marine and sub-marine vehicles propulsion system has to be divided into two independent subsystems responsible for movement in the horizontal and vertical planes respectively [10], [11]. Hierarchical architecture for the motion control of underwater vehicles, which encompasses strategic, tactical and execution levels of control has been proposed [12]. Planar motion control strategies have been developed adopting a dual-loop hierarchical guidance control schemes [13], [14]. An approach of planar motion steering of underwater vehicles equipped with longitudinal control surfaces which allow the drag coefficient modulation in the sway direction has been developed in [15]. Recently there has been widespread interest in the problem of cooperative motion control of multiple Autonomous Marine Vehicles (AMVs). An important scenario that motivates the cooperative motion control is the automatic ocean exploration, where there is inefficiency due to the fact a single underwater vehicle may need to wander significantly to collect data over a large spatial domain [16]. Cooperative group of ROVs (remoted operated Vehicles) can solve the problem above. The problem of multiple underwater vehicle control in the presence of severe communications constraints has been developed [17], [18]. Intelligent control has not been adressed in any of the papers above. About Fuzzy control strategies, a fuzzy like proportional derivative controller for ROV to control the yaw and the dept has been developed in [19]. A fuzzy hierarchical motion control for single ROV has been developed in [20], where a continuous time model for single underactuated ROV and hierarchical architecture which merge a low level kinetic controller with an high level fuzzy inference system have been presented for a single underwater vehicle.

In this paper we elaborate on the method developed in [21] with new results applied to autonomous semi-immergible DRONES. The following contributions are given:

1) A continuous time model for two-dimensional motion of DRONES, developed using polar coordinates, to consider the unactuated sway direction of each vehicle.

2) A new closed loop control system for DRONES, where the fuzzy controller generates the guidance laws in terms of surge speeds and yaw rates, needed to achieve the reference trajectories planned by the decentralized algorithm of the previous point. In this sense, Lyapunov's theory provides conditions on the fuzzy control surfaces under which the errors between the actual motion of each DRONE and the reference motion converge to zero, as regards the longitudinal and lateral positions and the orientations of each vehicle. The main advantages of the fuzzy approach are the robustness with respect to disturbance of the marine environment, the generation of forward surge speeds for the DRONES, and the saturation of all the control signals.

3) A kinetic controller which gives the surge forces and the yaw torques for each DRONE, to ensure the convergence of the actual speeds of all the underwater vehicles to the guidance commands given by the fuzzy controller of the previous point.

II. DRONE Mathematical models

Consider a platoon of r Drones. Fig.1 shows the assumed platoon configuration in open chain.

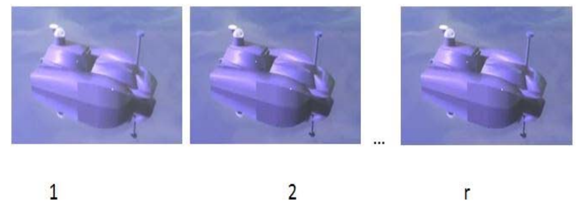

Figure 1: Platoon of Drones in open chain configuration

Let (X, Y) be the Earth Fixed Reference System (ERF) and $(x_{bi}, y_{bi}), i = 1...r$ be the fixed body frames of each Drone (cf. Fig. 2).

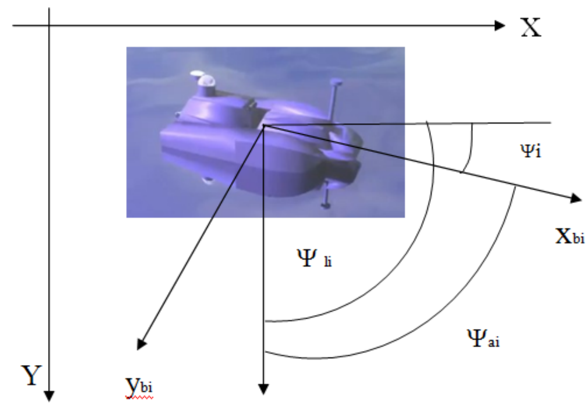

Figure 2. i-DRONE with reference systems.

Now the principal results of the mathematical model developed in [15] are extended for a platoon of r ROVs below. In the horizontal plane the following vectors have to be considered:

$$\begin{aligned} &\boldsymbol{\eta}_i(t) = [x_i(t) \;\; y_i(t) \;\; \psi_i(t)]^{\mathrm{T}}, \\ &\boldsymbol{\upsilon}_i(t) = [u_i(t) \;\; v_i(t) \;\; r_i(t)]^{\mathrm{T}} \\ &i = 1...r, \end{aligned} \tag{1}$$

where:

$x_i(t),\ y_i(t)$ represent the position coordinates with reference to the ERF of the i-Drone;

$\psi_i(t)$ represents the yaw, i.e. the orientation of the i-Drone;

$u_i(t),\ v_i(t)$ represent the surge and sway speeds respectively, i.e. the linear velocities along longitudinal and transversal axes evaluated in relation to the fixed body frame of the i-Drone ;

$r_i(t)$ represents the yaw rate, i.e. the angular velocity about the axis perpendicular to the plane (X,Y) of the i-Drone.

It results :

$$\dot{x}_i(t) = u_i(t)\cos\psi_i(t) - v_i(t)\sin\psi_i(t),$$
$$\dot{y}_i(t) = u_i(t)sen\psi_i(t) + v_i(t)\cos\psi_i(t), \quad (2)$$
$$\dot{\psi}_i(t) = r_i(t)$$
$$\mathrm{i} = 1...\mathrm{r}.$$

The presence of the sway speed is evident. It is responsible for translational motion with respect to the vehicle's longitudinal axis, so that equations (2) require integration of the unactuated dynamics to obtain the planar trajectory from the surge and angular velocities. Indicate the thruster surge force of the i-Drone with $\tau_{ui}(t)$ and the yaw torque with $\tau_{ri}(t)$. Indicate the mass of the i-ROV with m_i, the inertial moment about the axis perpendicular to the plane (x_{bi}, y_{bi}) with I_{zi} and the hydrodynamic masses with $X_{\dot{u}}, Y_{\dot{v}}$ and $N_{\dot{r}}$. The dynamic model results as it follows:

$$m_{ui}\dot{u}_i(t) - m_{vi}v_i(t)r_i(t) = \tau_{ui}(t),$$
$$m_{vi}\dot{v}_i(t) + m_{ui}r_i(t)u_i(t) = 0, \quad (3)$$
$$m_{ri}\dot{r}_i(t) = \tau_{ri}(t),$$
$$\mathrm{i} = 1...\mathrm{r},$$

where:

$$m_{ui} = m_i - X_{\dot{u}},$$
$$m_{vi} = m_i - Y_{\dot{v}}, \quad (4)$$
$$m_{ri} = I_{zi} - N_{\dot{r}},$$
$$\mathrm{i} = 1...\mathrm{r}.$$

Note that the sway force is unavailable, so that, to deal with this problem, the following polar coordinates transformation is defined (see Fig. 2):

$$u_{li}(t) = \sqrt{u_i^2(t) + v_i^2(t)},$$
$$\psi_{li}(t) = \psi_i(t) + \psi_{ai}(t), \quad (5)$$
$$i = 1...r,$$

where:

$$\psi_{ai}(t) = \arctan[v_i(t)/u_i(t)] \quad (6)$$
$$i = 1...r$$

are the sideslip angles of the vehicles.

Since the surge velocity is positive, it gives:

$$-0.5\pi \le \psi_{ai}(t) \le 0.5\pi, \quad (7)$$
$$i = 1...r.$$

The dynamical equations result as it follows:

$$\dot{x}_i(t) = u_{li}(t)\cos\psi_{li}(t),$$
$$\dot{y}_i(t) = u_{li}(t)\sin\psi_{li}(t),$$
$$\dot{\psi}_{li}(t) = r_i(t) + \dot{\psi}_{ai}(t) = r_{li}(t),$$
$$\tau_{ui}(t) = m_{ui}\dot{u}_{li}(t)/\cos\psi_{ai}(t) - m_{vi}v_i(t)r_i(t) +$$
$$+\frac{m_{ui}}{m_{vi}}r_i(t)u_i(t)\tan\psi_{ai}(t),$$
$$\tau_{ri}(t) = m_{ri}\dot{r}_i(t),$$
$$i = 1...r.$$

(8)

The accelerations of the i-Drone with respect to the body reference system may be written as it follows :

$$\begin{bmatrix} \ddot{x}_{\mathrm{Bi}}(t) \\ \ddot{y}_{\mathrm{Bi}}(t) \end{bmatrix} = \begin{bmatrix} \cos(\psi_{li}(t) - \psi_{ai}(t)) & \sin(\psi_{li}(t) - \psi_{ai}(t)) \\ -\sin(\psi_{li}(t) - \psi_{ai}(t)) & \cos(\psi_{li}(t) - \psi_{ai}(t)) \end{bmatrix} \begin{bmatrix} \ddot{x}_i(t) \\ \ddot{y}_i(t) \end{bmatrix} \quad (9)$$
$$\mathrm{i} = 1...\mathrm{r}$$

Practically each vehicle of the open chain configuration of Fig. 1 is equipped with an inertial navigation system which calculates the positions, velocities and accelerations of all the ROVs from an Inertial Measurement Unit (IMU). In the IMU there are accelerometers measuring specific force and gyros measuring angular rate. The output of the accelerometers gives data on the accelerations (9). Therefore the longitudinal and lateral positions may be evaluated by applying the inverse of (9) and then double integration, once the orientation of the ROV has been calculated from the data of the gyros. The mathematical model given by (8) will not be used to plan the trajectories. In Section III only geometrical considerations will be maded in order to plan circular trajectories. They will be used in Section IV to design the high level fuzzy system and the low level kinetic control. System requirement.

III. KINETIC SYSTEM FOR TWO-DIMENSIONAL PLANAR MOTION OF DRONES

A. Planar Motion Control problem for Drones

Consider the reference surge velocities and the reference yaw rates given by (16) in presence of a certain sideslip angle. Indicate the reference signals of each underwater vehicle with $u_{ri}(t)$ and $r_{ri}(t)$. They are without sideslip angle. Let the time varying coordinates of the reference trajectories evaluated in relation to the ERF be $x_{ri}(t), y_{ri}(t)$ and $\psi_{lir}(t)$. From equations (8) it is evident that the equations of the reference planar trajectories are the following:

$$\dot{x}_{ri}(t) = u_{lir}(t)\cos\psi_{lir}(t),$$
$$\dot{y}_{ri}(t) = u_{lir}(t)sen\psi_{lir}(t), \quad (17)$$
$$\dot{\psi}_{lir}(t) = r_{ri}(t) + \dot{\psi}_{ai}(t) = r_{lir}(t),$$
$$\mathrm{i} = 1...\mathrm{r}$$

where:

$$u_{ri}(t) = u_{lir}(t)\cos\psi_{ai}(t), \quad (18)$$
$$i = 1...r.$$

Indicate with $u_{ci}(t)$ and $r_{ci}(t)$ the surge velocities and yaw rates controls of each Drone respectively, while indicate with $u_{lic}(t)$ and $r_{lic}(t)$ the guidance control laws in the presence of sideslip angle. It yields:

$$\boldsymbol{\alpha}_{ci}^T(t) = [u_{ci}(t) \quad r_{ci}(t)],$$
$$0 < \sigma_{1i} \le u_{ci}(t) \le \sigma_{2i}, \quad (19)$$
$$\sigma_{i1}, \sigma_{2i} \in R^+$$
$$i = 1...r$$

and:

$$\boldsymbol{\beta}_{ci}(t) = \begin{bmatrix} u_{ci}(t)/\cos\psi_{ai}(t) \\ r_{ci}(t) + \dot{\psi}_{ai}(t) \end{bmatrix} = \begin{bmatrix} u_{lic}(t) \\ r_{lic}(t) \end{bmatrix} \qquad (20)$$
$$\mathrm{i} = 1 \ldots \mathrm{r},$$

Note that, once (7) has been verified, the control signals $u_{lic}(t)$ are positive every time if and only if the surge velocities $u_{ci}(t)$ are positive. If the speed of each ROV reaches the control velocity instantaneously, then the position and orientation of each vehicle may be obtained as it follows:

$$\begin{aligned} &\dot{x}_i(t) = u_{lc}(t)\cos\psi_l(t), \\ &\dot{y}_i(t) = u_{lc}(t) sen\,\psi_{li}(t), \\ &\dot{\psi}_{li}(t) = r_{ci}(t) + \dot{\psi}_{ai}(t) = r_{lic}(t) \\ &i = 1 \ldots \mathrm{r}.. \end{aligned} \qquad (21)$$

In any case the dynamical effects causes the impossibility of instantaneous reachability of the control velocities, so that indicate the surge force and the yaw torque control signals of each Drone with $\tau_{uic}(t)$ and $\tau_{ric}(t)$ and with $\boldsymbol{\alpha}_i(t)$ the following vectors :

$$\boldsymbol{\alpha}_i^{\mathbf{T}}(t) = [u_i(t) \;\; r_i(t)] \qquad (22)$$
$$\mathrm{i} = 1 \ldots \mathrm{r},$$

where $u_i(t)$ and $r_i(t)$ are the actual surge speeds and yaw rates. Let $u_{li}(t)$ and $r_{li}(t)$ be the same functions in the presence of sideslip angle.

The fuzzy controller proposed in this paper gives the guidance commands (20) for all the vehicles, and ensures the boundedness and convergence to zero of motion errors in relation to the body frame given by:

$$\mathbf{e}_i(t) = \begin{bmatrix} e_{xi}(t) \\ e_{yi}(t) \\ e_{\psi li}(t) \end{bmatrix} = \begin{bmatrix} \cos\psi_{li}(t) & \sin\psi_{li}(t) & 0 \\ -\sin\psi_{li}(t) & \cos\psi_{li}(t) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_{ri}(t) - x_i(t) \\ y_{ri}(t) - y_i(t) \\ \psi_{li\,r}(t) - \psi_{li}(t) \end{bmatrix} \qquad (23)$$
$$i = 1 \ldots r.$$

However the Fuzzy controller does not consider the dynamical effects. In particular the dynamics of the Drones are given by the fourth and fifth equations in (8); therefore it is necessary to consider a dynamical controller which gives the functions $\tau_{uic}(t)$ and $\tau_{ric}(t)$ to ensure convergence to zero of the errors given by the difference between the actual speeds and the fuzzy guidance control laws:

$$\begin{aligned} \bar{\mathbf{e}}_i(t) = \boldsymbol{\alpha}_{\mathbf{c}i}(t) - \boldsymbol{\alpha}_i(t) = \begin{bmatrix} e_{ui}(t) \\ e_{ri}(t) \end{bmatrix} = \begin{bmatrix} u_{ci}(t) - u_i(t) \\ r_{ci}(t) - r_i(t) \end{bmatrix} = \\ = \begin{bmatrix} (u_{lic}(t) - u_{li}(t))\cos\psi_{ai}(t) \\ (r_{lic}(t) - r_{li}(t)) \end{bmatrix} \end{aligned} \qquad (24)$$
$$\mathrm{i} = 1 \ldots \mathrm{r}.$$

B. Fuzzy control laws with Lyapunov's stability

The fuzzy system generates the guidance laws given by (19) and (20), where $u_{lc}(t)$ has to be saturated and must be a forward velocity, so that the Lyapunov's asymptotical stability of the tracking errors given by (23) is ensured. The fuzzy control laws for the multiple drones are the following:

$$\begin{aligned} &u_{ci}(t) = f_i(\mathbf{e}_i(t)) * \cos\psi_{ai}(t) + u_{ri}(t), \\ &r_{ci}(t) = [r_{ri}(t) + \dot{\psi}_{ai}(t)] + [u_{ri}(t)/\cos\psi_{ai}(t)] \times \\ &\qquad \times [g_i(\mathbf{e}_i(t)) + h_i(\mathbf{e}_i(t)) \sin e_{\psi li}(t)], \\ &u_{ci\max} \geq u_{ci}(t) \geq 0, \\ &u_{ri}(t) > 0 \quad \forall t, \\ &\mathrm{i} = 1 \ldots \mathrm{r} \end{aligned} \qquad (25)$$

where the nonlinear functions $f_i(\mathbf{e}_i(t))$, $g_i(\mathbf{e}_i(t))$ and $h_i(\mathbf{e}_i(t))$ are continuous and differentiable. The functions (20) are explicated as it follows:

$$\begin{aligned} &u_{lic}(t) = f_i(\mathbf{e}_i(t)) + u_{lir}(t), \\ &r_{lic}(t) = r_{lir}(t) + u_{lir}(t)[g_i(\mathbf{e}(t)) + h_i(\mathbf{e}(t)) \sin e_{\psi li}(t)], \\ &u_{lic\max} \geq u_{lic}(t) \geq 0, \\ &u_{lir}(t) > 0 \quad \forall t \\ &i = 1 \ldots r. \end{aligned} \qquad (26)$$

The functions $f_i(\mathbf{e}_i(t)), g_i(\mathbf{e}_i(t))$ and $h_i(\mathbf{e}_i(t))$ are associated to a single ROV of the open chain of Fig. 1 and they are the crisp outputs of fuzzy controllers. The Fuzzy inference systems are explained below. The following linguistic labels are defined:

S=Small;
M=Medium;
H=High;
Opp=Opposite.

The input and output Fuzzy memberships are generalized bell functions and they are shown in Figs. 5 and 6.

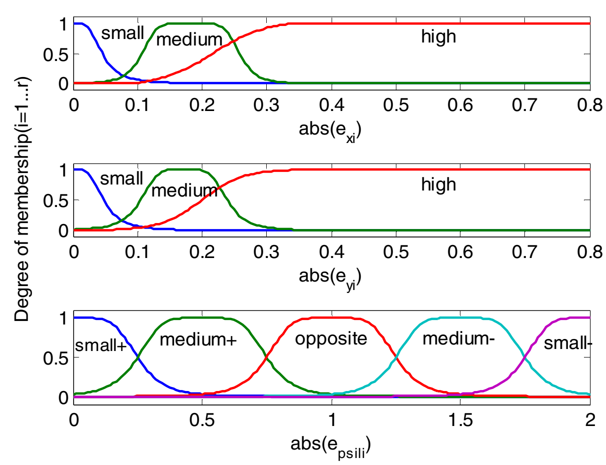

Figure 5. Input membership functions for multiple DRONEs

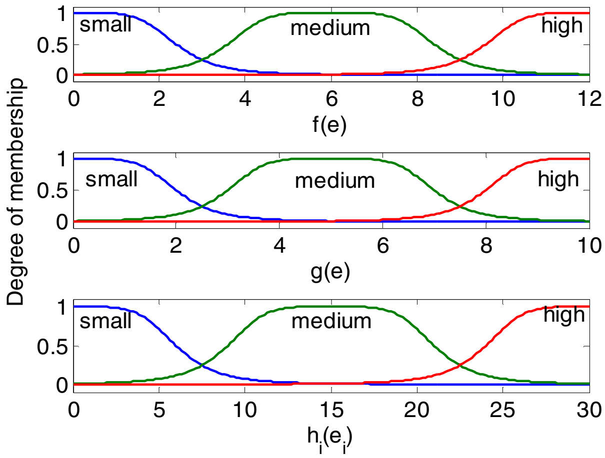

Figure 6. Output membership functions for multiple ROVs

Assumption 1. The membership functions have to be chosen in order to satisfy the following properties:

$$\text{Property 1:}\quad \begin{array}{l} f_i(\mathbf{e}_i(t))=0 \Leftrightarrow \mathbf{e}_i(t)=\mathbf{0}, \\ g_i(\mathbf{e}_i(t))=0 \Leftrightarrow \mathbf{e}_i(t)=\mathbf{0}, \\ h_i(\mathbf{e}_i(t))=0 \Leftrightarrow \mathbf{e}_i(t)=\mathbf{0}, \\ \mathrm{i}=1\ldots\mathrm{r}. \end{array} \tag{27}$$

$$\text{Property 2:}\quad 0 \le f_i(\mathbf{e}_i(t)) \le f_{i\max} \quad \mathrm{i}=1\ldots\mathrm{r} \tag{28}$$

$$\text{Property 3:}\quad 0 \le g_i(\mathbf{e}(t)) \le g_{i\max} \quad \mathrm{i}=1\ldots\mathrm{r}. \tag{29}$$

$$\text{Property 4:}\quad 0 \le h_i(\mathbf{e}_i(t)) \le h_{i\max} \quad \mathrm{i}=1\ldots\mathrm{r}. \tag{30}$$

$$\text{Property 5:}\quad \begin{array}{l} \sum_{j=0}^{M-1}\left[\int_j^{j+1} g_i(\mathbf{e}_i(t))dt\right] > 0, \\ j \in N, M>0 \\ i=1\ldots r. \end{array} \tag{31}$$

$$\text{Property 6:}\quad \begin{array}{l} \frac{\partial f_i(\mathbf{e}_i(t))}{\partial e_{xi}} > 0; \frac{\partial f_i(\mathbf{e}_i(t))}{\partial e_{yi}} \cong 0; \frac{\partial f_i(\mathbf{e}_i(t))}{\partial e_{\psi li}} \cong 0, \\ \frac{\partial g_i(\mathbf{e}_i(t))}{\partial e_{xi}} \cong 0; \frac{\partial g_i(\mathbf{e}_i(t))}{\partial e_{yi}} > 0; \frac{\partial g_i(\mathbf{e}_i(t))}{\partial e_{\psi li}} \cong 0, \\ \frac{\partial h_i(\mathbf{e}_i(t))}{\partial e_{xi}} \cong 0; \frac{\partial h_i(\mathbf{e}_i(t))}{\partial e_{yi}} \cong 0; \frac{\partial h_i(\mathbf{e}_i(t))}{\partial e_{\psi li}} > 0, \\ i=1\ldots r \end{array} \tag{32}$$

Remark 2. From the property (27) and from the first equation in (26), it yields:

$$u_{lir}(t)=\rho_{1i} \le u_{lic}(t) \le \rho_{2i} = f_{i\max} + u_{lir}(t), \quad \mathrm{i}=1\ldots\mathrm{r}, \tag{33}$$

where $f_{i\max}$ is the maximum value of the fuzzy function $f_i(\mathbf{e}_i(t))$ associated to the i-Drone. Note that the saturation value of the linear speed control of each underwater vehicle depends on the numerical value of $f_{i\max}$, so that the maximum values of each control signals may be regulated by varying the maximum value of each fuzzy function. Since the reference surge speed is positive, the linear control speed of the i-Drone is bounded and it is a forward command.

Now a reformulation of the theorem presented in [21] for single ROV, is presented in this paper for multiple DRONEs.

Theorem 1. Consider the mathematical model of the system constituted by r Drones as given by (21), in closed loop with the fuzzy control signals given by (26). Under the assumption 1, the equilibrium state of the closed loop system is the origin of the state space and it is asymptotically stable.

Proof. After some computations, the state space representation of the closed loop motion control system assumes the following form:

$$\dot{\mathbf{e}}_i(t) = \begin{bmatrix} (r_{lir}(t)+u_{lir}(t)g_i(\mathbf{e}_i(t))+h_i(\mathbf{e}_i(t))\sin e_{\psi li}(t))e_{yi}(t) + \\ +(f_i(\mathbf{e}_i(t))+u_{lir}(t)(1-\cos e_{\psi li}(t))) \\ -(r_{lir}(t)+u_{lir}(t)(g_i(\mathbf{e}_i(t))+h_i(\mathbf{e}_i(t))\sin e_{\psi li}(t))e_{xi} + \\ +u_{lir}(t)\sqrt{1-\cos^2 e_{\psi li}(t)} \\ -u_{lir}(t)(g_i(\mathbf{e}_i(t))+h_i(\mathbf{e}_i(t))\sin e_{\psi li}(t)) \end{bmatrix} \tag{34}$$

$\mathrm{i}=1\ldots\mathrm{r}.$

The equilibrium state of the representation (34) is the origin of the state space, once the property of the fuzzy functions given by (27) is verified. The following Lyapunov's function is chosen:

$$V_0=\sum_{i=1}^{r}\left(f_i(\mathbf{e}_i)+g_i(\mathbf{e}_i)\right)+\sum_{i=1}^{r}\left[(1-\cos e_{\psi li})\sum_{j=0}^{M-1}\left(\int_j^{j+1} g_i(\mathbf{e}_i(t))dt\right)\right] \tag{35}$$

Differentiating the function (35) and considering the properties given by (32), after some computations it yields:

$$\begin{aligned} \dot{V}_0 = &-\sum_{i=1}^{r}\frac{\partial f_i(\mathbf{e}_i(t))}{\partial e_{xi}}\left(f_i(\mathbf{e}_i(t)+u_{lir}(1-\cos e_{\psi li}))\right)+ \\ &+\sum_{i=1}^{r}\left(u_{lir}\sqrt{1-\cos^2 e_{\psi li}}\frac{\partial g_i(\mathbf{e}_i(t))}{\partial e_{yi}}\right)+ \\ &-\sum_{i=1}^{r}\left[\sqrt{1-\cos^2 e_{\psi li}}\,u_{lir}g_i(\mathbf{e}_i(t))\sum_{j=0}^{M-1}\left(\int_j^{j+1} g_i(\mathbf{e}_i(t))dt\right)\right]+ \\ &-\sum_{i=1}^{r}\left[u_{lir}h_i(\mathbf{e}_i(t))\sin^2 e_{\psi li}\sum_{j=0}^{M-1}\left(\int_j^{j+1} g_i(\mathbf{e}_i(t))dt\right)\right] \\ &+\sum_{i=1}^{r}\left[(1-\cos e_{\psi li})\sum_{j=0}^{M-1} g_i(\mathbf{e}_i(j))\right] \end{aligned} \tag{36}$$

Based on the properties (27)-(31), one may observe that the function (35) is definite positive. Assuming the reference linear velocities of all the Drones ($u_{lir}, i=1\ldots r$) are positive and considering the assumption 1, lead to the following mathematical relations:

$$0 \le \sum_{i=1}^{r} \left(\sqrt{1-\cos^2 e_{\psi li}}\, u_{lir} \frac{\partial g_i(\mathbf{e}_i(t))}{\partial e_{yi}} \right) <$$
$$< \sum_{i=1}^{r} \left[\sqrt{1-\cos^2 e_{\psi li}}\, u_{lir}\, g_i(\mathbf{e}_i(t)) \sum_{j=0}^{M-1} \left(\int_j^{j+1} g_i(\mathbf{e}_i(t))dt \right) \right] \tag{37}$$

$$\sum_{i=1}^{r} \left[u_{ri} h_i(\mathbf{e}_i(t))(1-\cos^2 e_{\psi i}) \sum_{j=0}^{M-1} \left(\int_j^{j+1} g_i(\mathbf{e}_i(t))dt \right) \right] >$$
$$> \sum_{i=1}^{q} \left[(1-\cos e_{\psi i}) \sum_{j=0}^{M-1} g_i(\mathbf{e}_i(j)) \right] \ge 0$$

Therefore function (36) is definite negative and the equilibrium point of model (34) is asymptotically stable.

C. Kinetic controller

The kinetic control generates the thruster surge force and the yaw torque control for the underactuated system of multiple underwater vehicles given by (8). The dynamics of the Drones implies the velocity errors given by (24), so that it is necessary to generate the dynamical control laws to ensure the convergence to zero of the errors above.

The following theorem may be formulated.

Theorem 2. Consider the underactuated system given by (8) in closed loop with the fuzzy guidance commands given by (26) and with the following dynamical control laws:

$$\begin{aligned}
&\tau_{ric}(t) = m_{ri}[\dot r_{lic}(t) - \ddot\psi_{ai}(t)] + \bar K_i m_{ri}[r_{lic}(t) - \dot\psi_{ai}(t) - r_i(t)],\\
&\tau_{uic}(t) = \frac{m_{ui}\dot u_{lic}(t)}{\cos\psi_{ai}(t)} + m_{ui}[r_{lic}(t) - \dot\psi_{ai}(t)]\times\\
&\quad\times \int_0^t [r_{lic}(t) - \dot\psi_{ai}(t)] u_{lic}(t)\cos\psi_{ai}(t)dt +\\
&\quad+ \frac{m_{ui}}{m_{vi}}\left[(r_{li}(t) - \dot\psi_{ai}(t)) u_{li}(t) \sin\psi_{ai}(t) \right] +\\
&\quad+ \frac{K_i m_{ui}}{\cos\psi_{ai}(t)}(u_{lic}(t) - u_{li}(t)),\\
&\bar K_i, K_i \in R^+\\
&i = 1...r.
\end{aligned} \tag{38}$$

where $\tau_{uic}(t)$ and $\tau_{ric}(t)$ are the surge force and the yaw torque controls of each ROV respectively, m_{ui}, m_{vi} and m_{ri} are given by (4), $u_{lic}(t)$ and $r_{lic}(t)$ are the fuzzy guidance commands given by (26), $u_{li}(t)$ and $r_{li}(t)$ are the actual velocities of each vehicle including the sideslip angle $\psi_{ai}(t)$ given by (6). Then the velocity errors given by (24) converge asymptotically to zero.

Proof. From the first equation of (38) and fourth and fifth equations of (8) it follows the following system of differential equations:

$$m_{ri}[\dot r_{lic}(t) - \ddot\psi_{ai}(t) - \dot r_i(t)] + \bar K_i m_{ri}[r_{lic}(t) - \dot\psi_{ai}(t) - r_i(t)] = 0 \tag{39}$$
$$i = 1...r.$$

Indicate whit $\theta_i(t)$ the following functions:

$$\theta_i(t) = r_{lic}(t) - \dot\psi_{ai}(t) - r_i(t) \tag{40}$$
$$i = 1...r,$$

The equations system (39) can be rewritten as it follows:

$$\dot\theta_i(t) + \bar K_i \theta_i(t) = 0 \tag{41}$$
$$i = 1...r.$$

Note that the functions $\theta_i(t)$ converge to zero rapidly if the constant $\bar K_i$ are sufficiently large. It yields:

$$\lim_{t\to\infty}[r_{ci}(t) - r_i(t)] = 0 \tag{42}$$
$$i = 1...r,$$

therefore the second component of the vector (24) converges asymptotically to zero. From the second equation of (3) the sway velocity of each vehicle results as it follows:

$$v_i(t) = -\frac{m_{ui}}{m_{vi}}\int_0^t r_i(t)u_i(t)dt = -\frac{m_{ui}}{m_{vi}}\int_0^t r_i(t)u_{li}(t)\cos\psi_{ai}(t)dt \tag{43}$$
$$i = 1...r,$$

Replacing (43) in the fourth equation of (8), and by choosing the surge force control that results from the second equation of (38), after some computations, it follows:

$$\begin{aligned}
&\frac{m_{ui}(\dot u_{lic}(t) - \dot u_{li}(t))}{\cos\psi_{ai}(t)} + \frac{K_i m_{ui}}{\cos\psi_{ai}(t)}[u_{lic}(t) - u_{li}(t)] +\\
&m_{ui}[r_{lic}(t) - \dot\psi_{ai}(t)]\int_0^t [r_{lic}(t) - \dot\psi_{ai}(t)]\, u_{lic}(t)\cos\psi_{ai}(t)dt +\\
&-m_{ui}[r_{li}(t) - \dot\psi_{ai}(t)]\int_0^t [r_{li}(t) - \dot\psi_{ai}(t)]\, u_{li}(t)\cos\psi_{ai}(t)dt = 0,\\
&i = 1...r.
\end{aligned} \tag{44}$$

Considering that the actual orientation of each ROV converges to the fuzzy guidance law (cf. eq. 42), in a steady state the equations (44) may be rewritten as it follows:

$$\begin{aligned}
&m_{ui}[\dot u_{ci}(t) - \dot u_i(t)] + K_i m_{ui}[u_{ci}(t) - u_i(t)] +\\
&+ m_{ui} r_i(t)\cos^2\psi_{ai}(t)\int_0^t r_i(t)[u_{ci}(t) - u_i(t)]dt = 0\\
&i = 1...r.
\end{aligned} \tag{45}$$

Now, the planned trajectories are circumferences, so that the steady state value of the actual yaw rates of all the vehicles are constant numbers. Indicate the values above with ρ_i (i=1...r). Equations (45) may be rewritten in function of the velocity errors given by the first component of (24) as it follows:

$$\ddot e_{ui}(t) + K_i \dot e_{ui}(t) + [\rho_i \cos\psi_{ai}(t)]^2 e_{ui}(t) = 0, \tag{46}$$
$$i = 1...r.$$

The eigenvalues associated to the differential equations (46) are given by the following equations:

$$\mu_i^2 + K_i\mu_i + [\rho_i\cos\psi_{ai}(t)]^2 = 0, \tag{47}$$
$$i = 1...r$$

The eigenvalues μ_i of each differential equation have to be real and negative, so the following constraints must be satisfied:

$$K_i > 2\rho_i\sqrt{0.5\pi}, \tag{48}$$
$$i = 1...r.$$

Once the constraints given by (48) are satisfied, the solutions of the equations system (47), i.e. the first component of the vector (24), converge asymptotically to zero.

V. SIMULATION EXPERIMENTS

In this section simulation in Matlab environment have been performed, where the efficiency of the motion control system and the effectiveness of the planning algorithm are shown in case of two identical ROVs.

The parameters of the underwater vehicles have been chosen based on existing underwater vehicles [22]. The nominal parameters of the DRONEs are as follows:

$$\begin{aligned} &m_i = 30kg, \\ &X_{\dot{u}i} = Y_{\dot{v}i} = 29.4462\,kg, \\ &N_{\dot{r}i} = 1.5423\,kg \cdot m^2, \\ &I_{zi} = 0.27\,kg \cdot m^2, \\ &i = 1,2. \end{aligned} \tag{49}$$

The numerical values of the fuzzy memberships are shown in Figs. 5 and 6, while Fig.8 shows the fuzzy surfaces $f_i(\mathbf{e}_i(t)), i = 1,2$. The fuzzy surfaces $g_i(\mathbf{e}_i(t))$ and $h_i(\mathbf{e}_i(t))$ have the same symmetry of $f_i(\mathbf{e}_i(t))$.

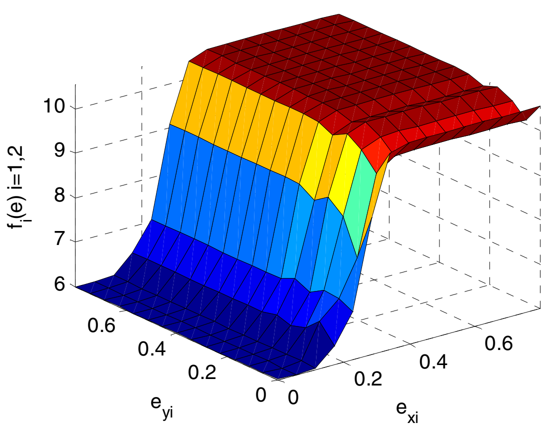

Figure 8. Fuzzy control surface of the ROVs.

The reference trajectories of each vehicle were generated using the algorithm developed in Section III. Initially the ROVs are in open chain configuration along x-direction. All the generalized coordinates of the motion of the ROVs are shown in Fig. 9.

The initial positions of the two vehicles are as follows:

$$\begin{aligned} &x_1(t=0) = 40m; \\ &x_2(t=0) = 80m; \\ &y_1(t=0) = 20m; \\ &y_2(t=0) = 20m; \\ &\psi_{l1}(t=0) = 1{,}74rad; \\ &\psi_{l2}(t=0) = 1.74rad. \end{aligned} \tag{50}$$

The position coordinates of the target are:

$$\begin{aligned} &x_T = 30.7m; \\ &y_T = -40m. \end{aligned} \tag{51}$$

In the planar motion the depth of all the vehicles is constant and it is assumed as it follows:

$$\begin{aligned} &z_i = -15m, \\ &i = 1,2. \end{aligned} \tag{52}$$

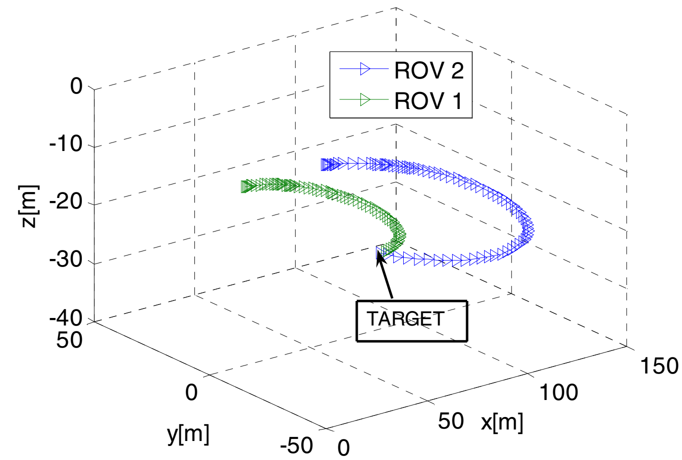

Figure 9. Planar motion of the ROVs.

Remark 3. Note that there are not intersections between the trajectories, so that there are not collisions between the vehicles during the motion.

Figures 10 and 11 show the motion errors given by (23) and the sideslip angles given by (6).

Remark 4. Observing Figs. 10 and 11, it is evident that the ranges of the errors of the fuzzy memberships shown in Figs 5,6 and 8 cover the values of the motion errors of each vehicle. The motion errors are equal to zero initially. Due to the dynamics of the underwater vehicles, there is a certain delay time before reaching the steady state. Therefore, after just a short time, the longitudinal and lateral motion errors are subjected to very small oscillations around the equilibrium state, while the orientation errors converge to zero. The values of the sideslip angles are in the range shown in (7).

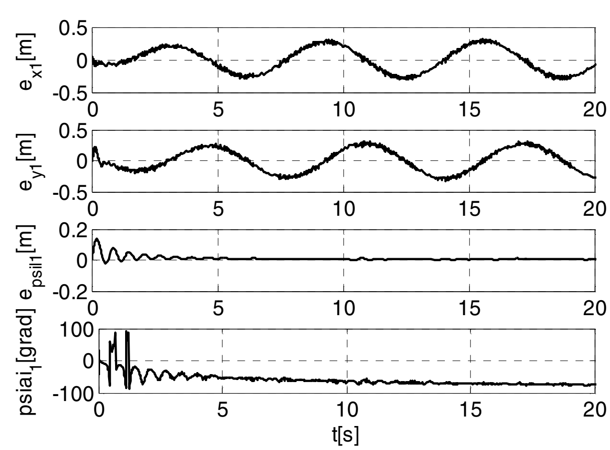

Figure 10. Motion errors and sideslip angle of the drone 1.

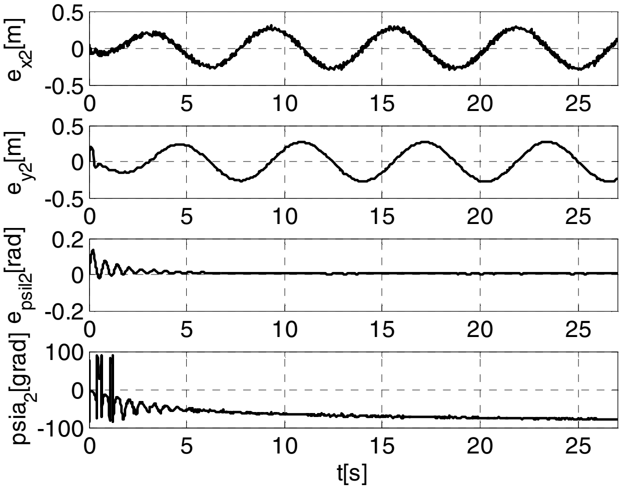

Figure 11. Motion errors and sideslip error of the drone 2.

In Fig. 12 and 13 the fuzzy guidance commands given by (26) and the velocity errors of the two vehicles given by the first and second components of the vector (24) are plotted.

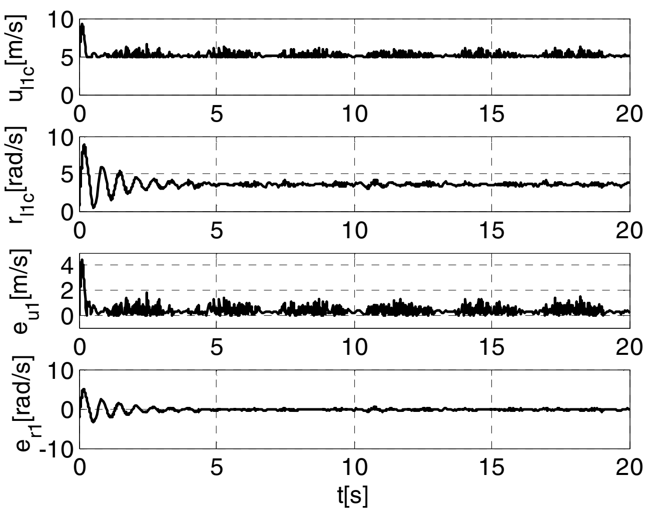

Figure 12. Fuzzy guidance commands and velocity errors of drone 1.

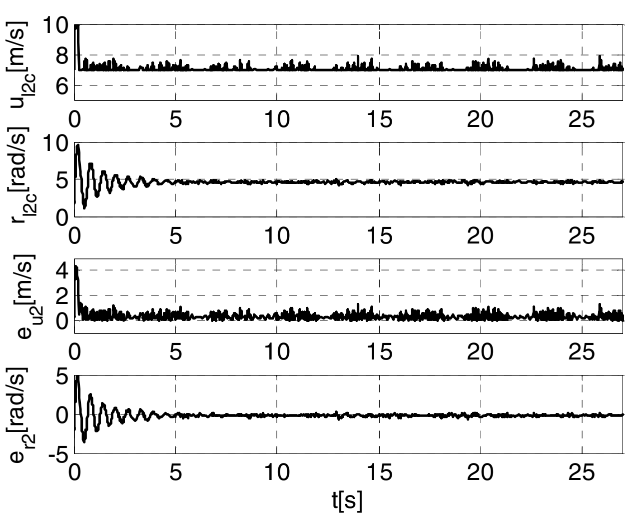

Figure 13. Fuzzy guidance commands and velocity errors of drone 2.

Remark 5. Observing Figs 8, 12 and 13 it is evident that the fuzzy control velocities given by the first equation of (26) are in the range shown in (33). It yields:

$$u_{l1r}(t) = 5 = \rho_{11} \le u_{l1c}(t) < \rho_{21} = f_{1\max} + u_{l1r}(t) = 12 + 5$$

$$u_{l2r}(t) = 7 = \rho_{12} \le u_{l2c}(t) < \rho_{22} = f_{2\max} + u_{l2r}(t) = 12 + 7 \quad (53)$$

The maximum values of the velocities above are lower than the saturation values, because the values of the motion errors of the ROVs are smaller than the expected maximum values of the errors in the fuzzy memberships. Note that the fuzzy linear velocities are forward commands. Due to the dynamics of the underwater vehicles the velocity errors have an initial transient state, where they are not equal to zero.

Figs. 14 and 15 plot the surge forces and the yaw torque control signals given by the dynamical control laws (38).

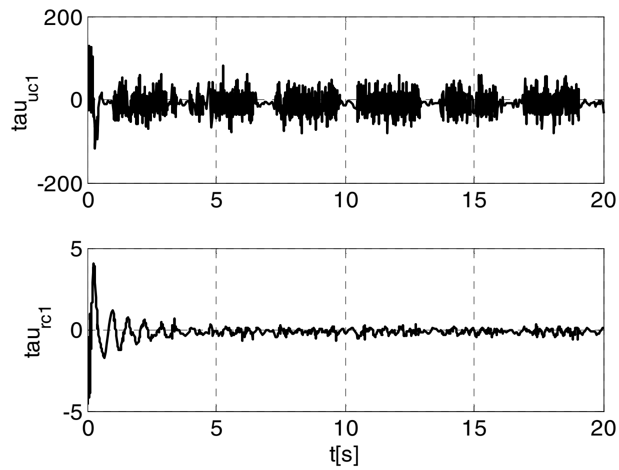

Figure 14. Surge force control and yaw torque control of drone 1.

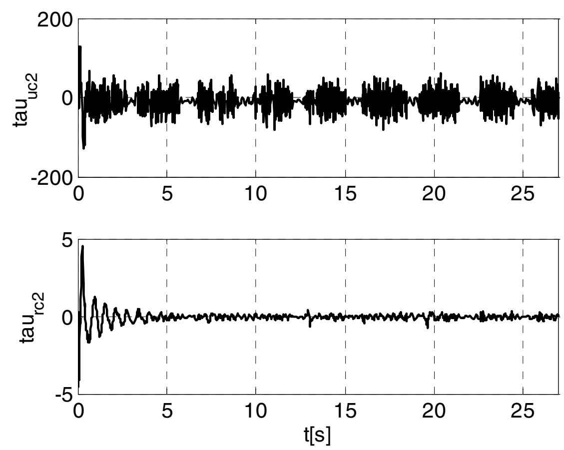

Figure 15. Surge force control and yaw torque control of drone 2.

Remark 6. Fig 16 shows how the closed loop control system compensates the external disturbances, so that it shows the robustness of the proposed control system.

VI. EXPERIMENTS AND TESTING

The current model has been the subject of an upgrade as regard the qualities of stability [6] by equipping two active stabilizers automatically controlled, shows in Fig.17, 18 for increased safety during the steering angle operation. Another upgrade of the propulsion, through a new electric motor Fig.20, that provides, in the very silent mode, the transmission to the engine of a high pressure water jet. All control actions are doubled to provide an intrinsically safe operation during the missions carried out by people around the operation of the drone.

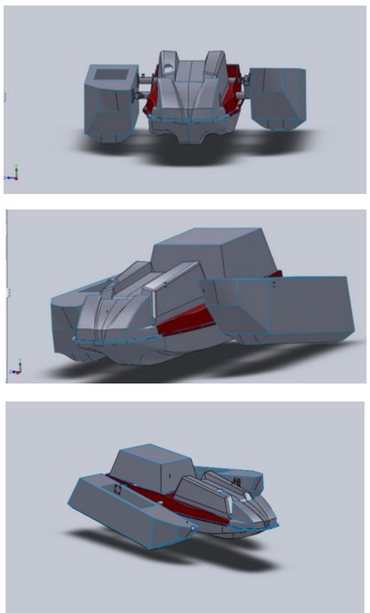

Fig. 17– SI-USV designed and played by built with Solid Work programs

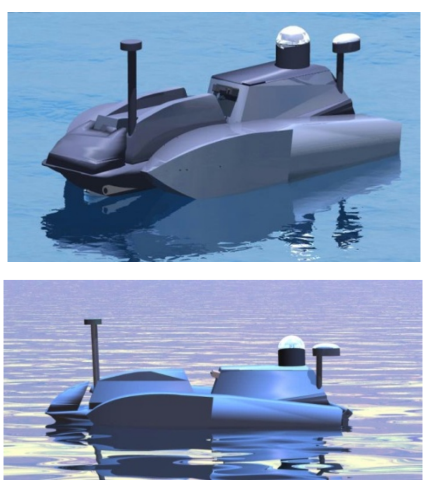

Fig 18.– SI-USV designed and played by 3D simulation

The figure n.19 in 3D simulation shows the innovative Semi-Immersible features sequence, figure .

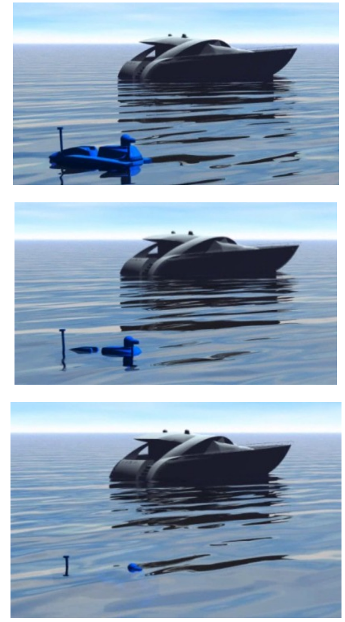

Fig.19– SI-USV Semi-Immergible features sequence

Fig.20- The figures refer to the realized and manufactured and tested at Piana degli Albanesi Lake (PA-IT) with electrict motor

VII. Conclusions

In this paper a new fuzzy control for two dimensional motion of SI-USV Drones has been presented. To consider the unactuated sway directions of each vehicle, the mathematical model of the vehicles has been developed using polar coordinates. The fuzzy guidance commands of each vehicle ensure forward surge speed control and saturation of all the control signal. The Lyapunov's stability of the equilibrium state of the fuzzy closed loop control system has been demonstrated. This ensures the stabilization of all the vehicles in the planned trajectories. The kinetic controller ensures the convergence of the fuzzy guidance commands to the actual speed of each cooperative Drone. Simulation experiments show the effectiveness of the proposed trajectory planning and control algorithm and the robustness with respect to outside disturbances violating the nominal motion of the Drones.

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